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Title: PULSED POWER HYDRODYNAMICS: A NEW
APPLICATION OF HIGH MAGNETIC FIELDS

Author(s): Robert E. Reinovsky (DX-DO), Wallace E. Anderson
(MST-7), Walter L. Atchison (X-1), Rickey J. Faehl (X-1),
Rhonald L. Keinigs (X-4), Irvin R. Lindemuth (X-1), David W.
Scudder (P-22), Jack S. Shlachter (P-DO), Antoinette J.
Taylor (MST-10)

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Pulsed Power Hydrodynamics: A New Application of High Magnetic Fields[*]

R.E. Reinovsky, W.E. Anderson, W.L Atchison, R.J. Faehl, R.K. Keinigs,
I.R. Lindemuth, D.W. Scudder, J.S. Shlachter, A.J. Taylor

Los Alamos National Laboratory
PO Box 1663
Los Alamos, New Mexico USA

Abstract

Pulsed Power Hydrodynamics is a new application of high magnetic fields recently developed to explore advanced hydrodynamics, instabilities, fluid turbulences, and material properties in a highly precise, controllable environment at the extremes of pressure and material velocity. The Atlas facility at Los Alamos is the world's first and only laboratory pulsed power system designed specifically to explore this relatively new family of megagauss magnetic field applications. Constructed in 2000 and commissioned in August 2001, Atlas is a 24-MJ high-performance capacitor bank delivering up to 30 MA with a current risetime of 5–6 μsec. The high-precision, cylindrical, imploding liner is the tool most frequently used to convert electrical energy into the hydrodynamic (particle kinetic) energy needed to drive the experiments. For typical liner parameters including initial radius of 5 cm, the peak current of 30 MA delivered by Atlas results in magnetic fields just over 1 MG outside the liner prior to implosion. During the 5 to 10-μsec implosion, the field outside the liner rises to several MG in typical situations. At these fields the rear surface of the liner is melted and it is subject to a variety of complex behaviors including: diffusion dominated and/or melt wave field penetration and heating, magneto Raleigh-Taylor sausage mode behavior at the liner/field interface, and azimuthal asymmetry due to perturbations in current drive.

The first Atlas liner implosion experiments were conducted in September 2000 and 10–15 experiments are planned in the first year of operation. Immediate applications of the new pulsed power hydrodynamics techniques include material property topics including: exploration of material strength at high rates of strain, material failure including fracture and spall, and interfacial dynamics at high relative velocities and high interfacial pressures. A variety of complex hydrodynamic geometries will be explored and experiments will be designed to explore unstable perturbation growth and transition to turbulence. This paper will provide an overview of the range of problems to which pulsed power hydrodynamics can be applied and the issues associated with these techniques. Other papers at this Conference will present specifics of individual experiments and elaborate on the liner physics issues.

I. INTRODUCTION

The last few years have seen a new application for ultra high magnetic fields called pulsed power hydrodynamics beginning to emerge. In this new application, very high magnetic fields, produced by very large electrical currents, are used in a fairly traditional way (the classic z-pinch geometry) to implode a relatively thin-walled conducting cylinder called a liner, to high velocity while maintaining the imploding material at near solid density—and largely un-melted. The imploding liner is then used, as shown in Fig. 1, to deliver a strong shock to a target located near its center; to perform work by large volume compression on a magnetic field, magnetized plasma, or other working fluid to dramatically increase its

internal energy density; or to shocklessly pressurize a target material that is either the liner itself or that is initially in contact with the liner. The new feature of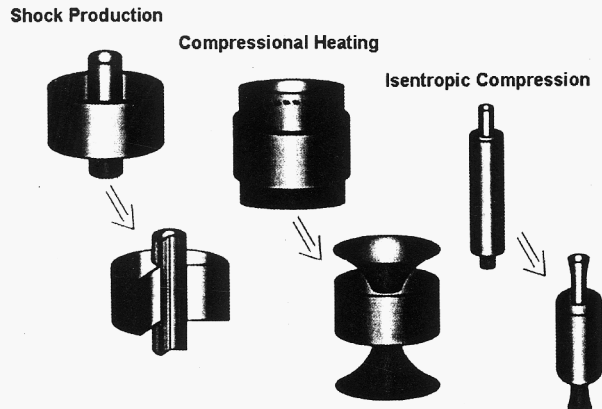 pulsed power hydrodynamics is the precision with which the implosions can be conducted. Liner implosions maintaining circularity to far better than 1% of initial radius and maintaining axial uniformity to the limit of imaging resolution are now common. This unprecedented precision allows liners to be employed as drivers for hydrodynamics and material properties experiments adding experiments in converging geometry to a field where planar impact (e.g., from light gas guns) has long been the standard.

Shock Production

Compressional Heating

Isentropic Compression

Figure 1. Precision liner implosions can be used to produce strong shocks, to compressionally heat by PdV work or to isentropically compress a sample.

specifically designed and optimized to conduct pulsed power hydrodynamics experiments and entered experimental service in September 2001. Atlas is capable of delivering 30-MA currents in a heavily damped sinusoidal waveform with 5 to 6-µs risetime and is ideal for driving liners with initial radius up to 10 cm and whose length may range from a few to a few tens of cm.

II. LINERS

Magnetically imploded liners, shown schematically in Fig. 3, offer unique advantages as drivers for pulsed power hydrodynamics experiments. Because energy is delivered to the liner from the magnetic field at the
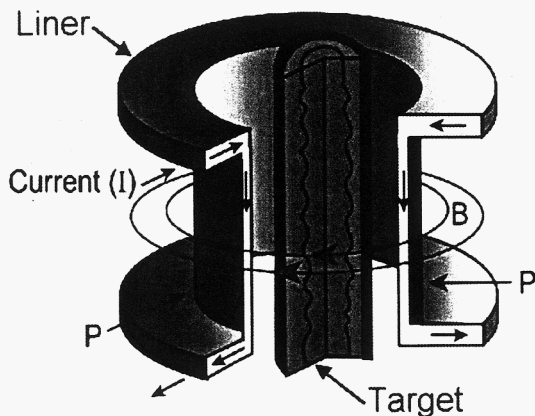
The most attractive pulsed power system for driving such experiments is an ultra-high current, low impedance, microsecond time-scale source that is both economical to build and reliable to operate. The Atlas system,[1] shown in Fig. 2, is the world's first pulsed power system to be
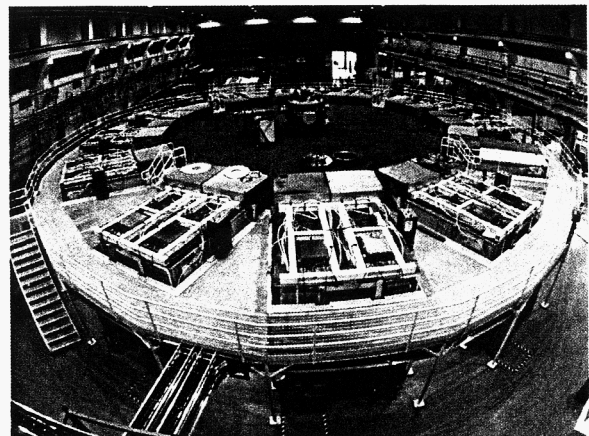
Figure 2. The Atlas pulsed power system.

Figure 3. Schematic liner and target geometry.

speed of light, magnetically imploded liners can reach velocities higher than those available from gas guns or planar explosive systems. Higher velocity in the liner (impactor) means higher pressures and temperatures in the target. Because the parameters of the electrical drive can be continuously adjusted over a wide range, the liner acceleration profile and hence final velocity can be continuously and controllably varied to meet experimental requirements. Furthermore, with appropriate design, the acceleration delivered by the field to the liner is nearly shockless, allowing the condition of the liner to be well characterized when it impacts the target. The size of magnetically driven liners naturally couples to targets of centimeter sizes. At these scales the target is many times the characteristic

size of grains in the target material allowing reliable probing of continuum properties. The fundamentally cylindrical geometry permits good diagnostic access both down the axis of the cylinder and transverse to it. The cylindrical geometry allows a variety of special initial conditions such as axial and azimuthal perturbations and a range of interfacial geometries to be studied.

The first Atlas experiments were designed to verify the fundamental dynamics of liners imploded with approximately 20-MA currents. The initial liner radius was 5 cm; its height was 4 cm; and its thickness was 1.2 mm. A photograph of a liner is shown in Fig. 4. During its implosion, the liner shape was monitored by transverse radiography[2] and the inner surface trajectory and velocity by laser velocimetry (VISAR).

As shown in Fig. 5, the liner velocity after 5:1 convergence was found to be 7.5 km/sec in good agreement with 1D calculations. Reproducibility was evaluated by comparing two consecutive experiments of identical construction and driven with identical currents and found to be excellent. Imaging disclosed the development of unpredicted perturbations on the back surface of the liner beginning just after 8.5 µsec, when the liner had moved about 15 mm. The amplitude of the 0.5 to 2.0-mm wavelength perturbations grow sufficiently to penetrate nearly to the inner surface of the liner in 2–3 µsec after they are first detectable on the outer surface. At that time, the liner has reached its "target" radius of 10 mm. Inner surface velocity of the liner tracked 1D calculations very accurately (and consistently) until the apparent emergence of the perturbations apparently disrupted the inner surface.

10 cm diameter liner
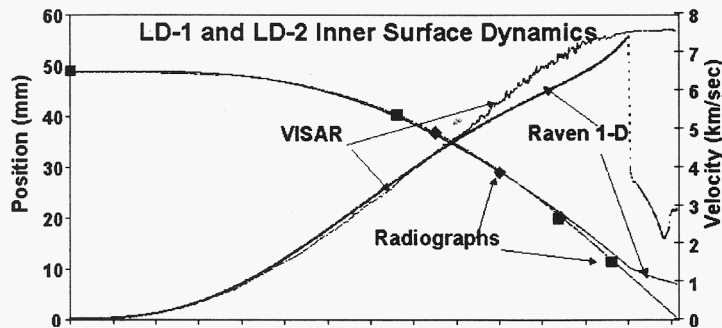
Figure 3. Schematic liner and target geometry.

Figure 5. Liner inner surface position and velocity from VISAR compared to from radiography on two consecutive experiments.

Because liners of identical composition and construction had been successfully imploded using 15-MA drive on the Shiva Star capacitor bank at the Air Force Research Laboratory in the year preceding Atlas commissioning[3] with excellent uniformity and shape, the occurrence of rear surface perturbation growth on the Atlas experiments was surprising. Furthermore, the same 2D MHD simulations (employing material strength in the liner) that had successfully predicted the qualitative and quantitative growth of preformed perturbations on Pegasus,[4] predicted no such perturbation growth under Atlas conditions. It was found, as shown in Fig. 6, that among three generally used equations of state from the SESAME family of material models one model (3715, the one used for simulating the Pegasus experiments) dramatically under-predicted the rate of perturbation growth in the Atlas experiments, and one (3717) dramatically over-predicted the rate of growth. Computational evaluation found that yet another equation of state (3719) was best for predicting Atlas liner performance, and its use allowed for the choice of operating parameters that led to implosions generally free from perturbation growth.
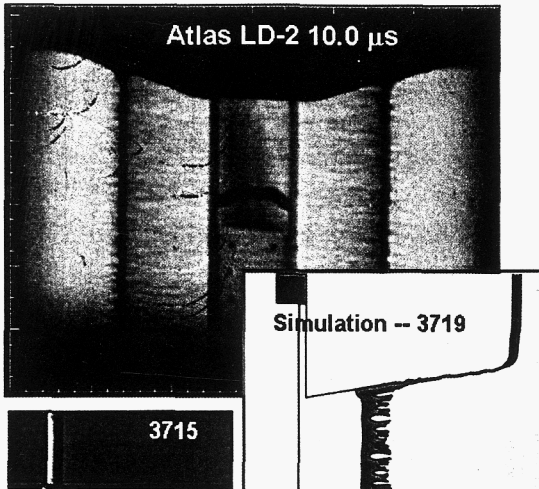
Figure 6. Radiograph showing outer surface perturbations and simulations performed with three different equations of state.

While the exact phenomenology that distinguished the various EOS models is still under investigation, one possible explanation relates to the path the material takes through thermodynamic phase space as the magnetic field (and hence pressure) on the back surface of the liner drops when the current falls in the second quarter period of the driving waveform. In all cases the driving current heats the back surface of the liner to melting but the hot liquid is confined by the magnetic pressure and cannot expand until the pressure begins to drop. The somewhat faster Atlas waveform (compared to Shiva Star) means that at the same radial convergence, the Atlas current has fallen to a lower value in the second quarter period and the material is expanding against a lower (almost zero) pressure. This provides the opportunity for the material to expand into a two-phase region, undergoing a rapid (and non-uniform) phase change that seeds the perturbation growth. At higher pressure, (above the critical point) the two-phase region does not exist, the material transitions smoothly from liquid to vapor without seeding the perturbations. The different equations of state treat the two-phase behavior differently, and that may explain their different behavior in predicting liner performance.

When applied to Atlas drive conditions, Sesame 3719 allowed adjustment of drive parameters to achieve the smooth, uniform implosion needed for pulsed power hydrodynamic experiments, as shown in Fig. 7. Transmission radiographic images permit visual evaluation of the quality of the imploding liner, but detailed interpretation of the, assumed cylindrically symmetric, liner is required for detailed comparison with 2D calculations. Improvements in radiographic imaging, compared to Pegasus data, permit application of an Abel Inversion to the transmission images recovering density information. Figure 8 shows sufficient detail in the results of the Abel analysis to discern details such as a "foot" that precedes the liner along the, slightly inclined, high-density electrodes and a "tail" of liner material left behind as the liner moves.

Such detailed analysis also allows evaluation of the precision of liner implosion, such as the amount by which the dynamic center of the liner implosion departs from perfect concentricity with the target geometry. Early experiments showed 200 to 400-μ non-concentricity ($\Delta r/r \sim 1$–2%). This asymmetry is tentatively attributed to asymmetry in the current drive delivered to the liner perhaps resulting from non-uniformities in current contacts either in the liner or in the hardware delivering current to the liner. While 2D (r-z) MHD simulations, with assumed θ symmetry in current and magnetic field are routine, the related (r-θ) MHD problem with non-symmetric currents is not as simple—and indeed is, in fact, correctly a 3D (r-θ–z) problem.
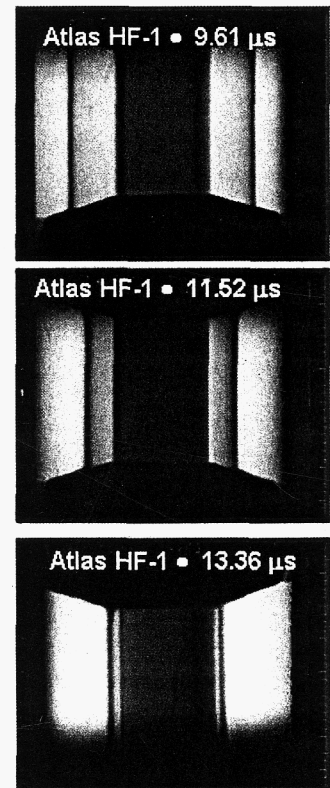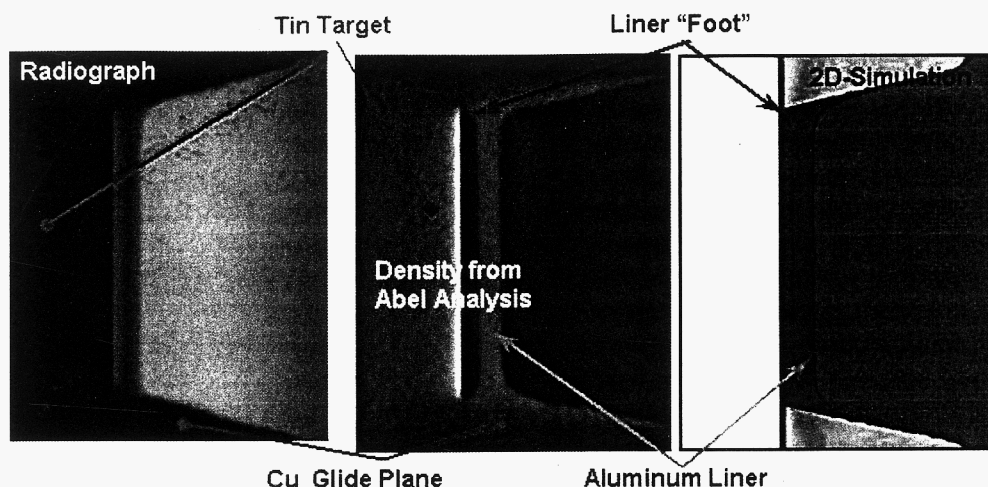

Figure 7. Precision implosion

Figure 8. Photographic radiographic data (left), converted to local material density by applying an Abel Inversion (center) and a 2D simulation of the implosion (right).

III. PULSED POWER HYDRODYNAMIC EXPERIMENTS

Liner-driven pulsed power hydrodynamics techniques can be applied to a wide variety of interesting questions broadly addressing the properties and behavior of condensed matter and plasmas. Generally, these topics fall into three categories: (1) the properties of condensed matter at extremes of pressure, temperature, and energy density; (2) the hydrodynamic behavior of imploding systems; and (3) the properties and behavior of dense plasmas. In the first category, pulsed power driven liner experiments can explore the equation of state of materials and phase transitions under single shock (Hugoniot) conditions, ultimately at higher shock pressures than those attainable by gas-gun and flyer-plate techniques. Magnetic drive offers access to shockless compression techniques[5][6][7] that can reach material states not accessible through a single shock process (off-Hugoniot conditions). During implosion, the material in the liner reaches strains and rates of strain far exceeding those available from other techniques, and liner implosions enable the study of the effects of material strength and material failure at surfaces (ejecta) and in bulk (spall), under unprecedented conditions. In the second category, implosion hydrodynamics, liner driven experiments are excellent for exploring instability growth in materials displaying full strength and in strengthless materials, the behavior of material at interfaces (friction) and hydrodynamic flows in complex geometries. In the third category, plasmas in which the ion and electron physics are strongly coupled are difficult to produce and little experimental data are available. The extremely high liner implosion velocities accessible with magnetic drive can conceptually produce plasmas characterized by $\Gamma < 1$ and $\Theta > 1$ for the study of thermodynamic and transport properties, in such strongly coupled plasmas. Realistically, only a limited number of these topics can be addressed at the outset and those selected for early exploration on Atlas include material strength and failure (spall), interfacial dynamics (friction), and complex hydrodynamic flows.

Material Properties

Pulsed power driven liner hydrodynamics provides a unique opportunity to study the strength and ultimately, the failure of materials under extreme conditions. Liner implosions offer unique access to simultaneous conditions of high strains and strain rates with nearly continuous access to a wide range of parameters. Because of cylindrical convergence, the inner surface of an imploding Atlas liner can reach strains exceeding 200% at strain rates of 10^4 to 10^6 per second—a regime unreachable by any other technique. By proper choice of liner parameters (e.g., a high conductivity aluminum armature

surrounding a thinner cylinder of the material of interest) the test sample can be isolated from the effects of the drive (including ohmic heating) and the acceleration can be applied in such a way as to insure that the sample material is not shocked. With only a slight increase in complexity, the introduction of a third, intermediate, layer between liner and sample further isolates the sample from processes happening in the liner and allows additional control of the pressure history applied to the target. (Barns pioneered such studies using high explosive drive and the growth of perturbations on the outer surface of the sample materials as a diagnostic of material strength in 1974.[8]) For Atlas studies of material strength, a "three-layer liner" shown in Fig. 9, has been designed by a joint LANL/VNIIEF team employing an aluminum, current-carrying liner; a polyethylene intermediate layer, and a copper sample. Perturbations of a few hundred microns in amplitude and a few millimeter wavelengths are pre-formed (machined) into the outer surface of the sample. The perturbations can be detected by radiography before acceleration and are predicted to grow in amplitude by a factor of 2–8 during approximately 8 μs of drive, as shown in Fig. 10. While not producing directly interpretable material strength parameters, the growth observable in these experiments is predicted to distinguish between several material models and among different computational techniques.
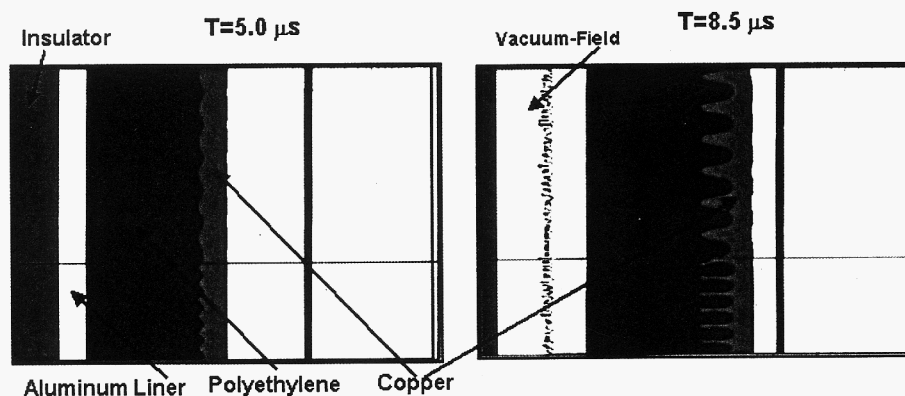

Figure 9. "Three-layer-liner" concept for exploding material strength using growth of perturbations at the interface between the plastic intermediate layer and the copper sample.
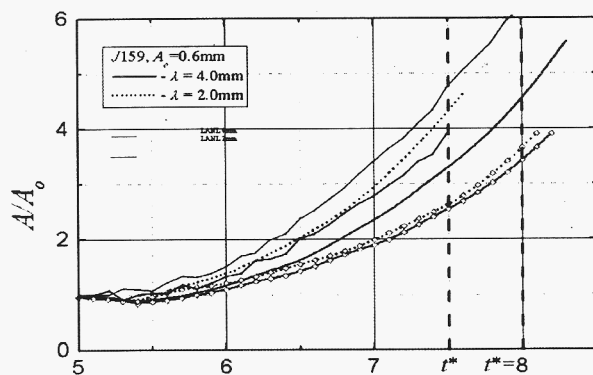

Figure 10. Growth of preformed perturbations as predicted by two material model using both LANL and VNIIEF computational techniques.
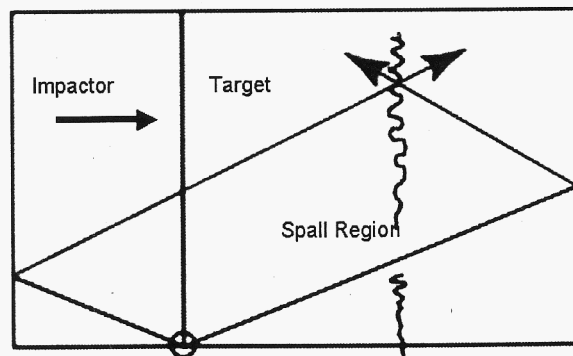

Figure 11. Free surface velocity data from one spall experiment, at two locations. These data imply a spall strength in the aluminum of 10.5 kbar.

Liner implosions also offer unique opportunities for studying material failure (ultimate strength) at very high strain rates (in shocks) at pressures from just below the failure threshold to those many times the failure threshold. One convenient and familiar geometry for studying failure is the intersecting shock geometry leading to "spall." In this geometry, shown schematically in Fig. 11, a flyer (liner) hits a target

producing a forward running compressional shock in the target and a reverse running shock in the flyer. If the forward running wave encounters a free surface, it reflects as a rarefaction wave dropping the pressure in the target material to zero. Similarly, the reverse running shock reflects from the rear surface of the impactor, providing another (forward-going) rarefaction wave in the target (and impactor) material. When the two rarefaction waves meet, a few millimeters behind the target inner free surface, the target material is placed in tension and (if the tension is sufficient) the target material fails (spalls). A series of four Atlas experiments have been conducted using a specially characterized, grain-oriented aluminum target material (driven by an identical aluminum liner) at shock pressures of 45, 65, and 80 kbar. With these parameters, the tension in the sample is expected to span the range where the material is subjected only to the first stages of failure (insipient spall) to parameters where the sample clearly fails. Experiments conducted on Pegasus have explored even higher pressure failure, but in material that was less well characterized than that used in the Atlas experiments. Material behavior is diagnosed by monitoring the (inner) free surface velocity (using VISAR). Figure 12 shows VISAR measurements of inner surface velocity at two points. The VISAR shows the first shock breakout. The "pull back" as material is placed in tension and ringing after material failure. From peak velocity and velocity at failure, a spall strength can be found. In addition to VISAR, both transverse and longitudinal radiography is used to image the formation of the spall layer. Post-failure metallurgy, as shown in Fig. 13, provides important information about the behavior of the material during a spallation event. The controllability of pulsed power driven liners allows recovery of both native material and, in some cases, even the spalled material for post event analysis—and this is a significant advantage.
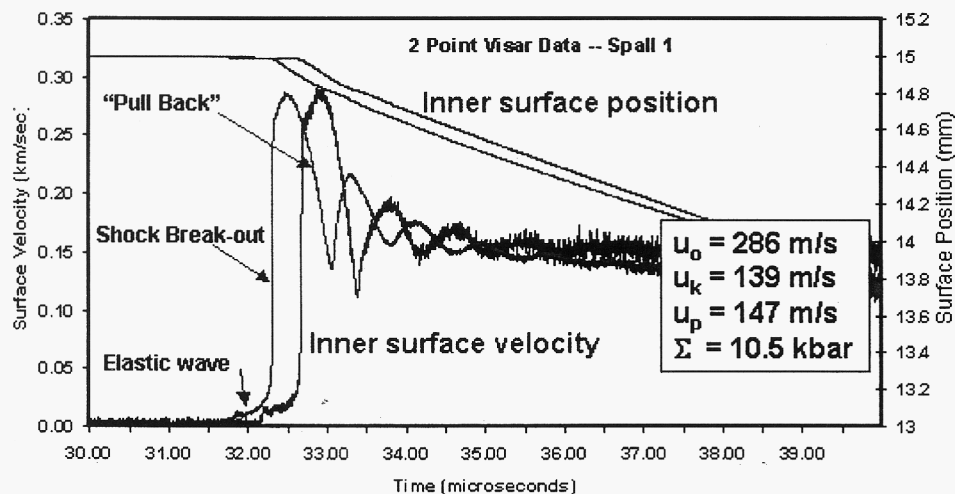

Figure 12. Free surface velocity data from one spall experiment at two locations. These data imply a spall strength in the aluminum of 10.5 kbar.

Implosion Hydrodynamics

After the planar (Cartesian) geometry, the symmetrical (cylindrical) imploding geometry is one of the next most fundamental dynamic systems whose behavior is of interest and the magnetically imploded liner is an ideal driver for fundamental implosion experiments. Cartesian geometry is traditionally used to explore material properties and their study in converging, liner-driven geometry, described
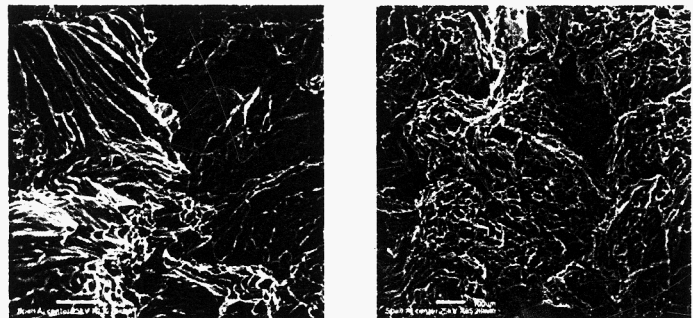

Figure 13. Post-shot micrographs of failed material.

above, represents a departure from and extension of that traditional approach. Symmetrical, radially imploding geometries can be readily simulated and a relatively large family of elementary questions emerge from the need to benchmark (both old and new) hydrodynamic simulation techniques. Experimental data from configurations that are readily definable and calculable, but for which analytic solutions are not available, are important in these benchmarking efforts. The five-shot Atlas Hydro-features series (preceded by the four-shot Near Term Liner Experiments[9] series on Shiva Star) addresses these questions, demonstrating a sophisticated suite of experimental diagnostics for liner-driven experiments in the process. Both of these series employ a high-precision, shocklessly accelerated, aluminum liner symmetrically colliding with a tin shock receiver. The collision launches cylindrical shock in the receiver, and since the properties of both aluminum and tin on the principal Hugoniot are well known, the shock is both well defined and well characterized. Tin melts at relatively low shock pressure and, for the parameters chosen, the tin is in a strength-free liquid state. The converging shock emerges from the tin into a lower density, optically transparent medium (acrylic or water) where its motion is characterized by two diagnostics simultaneously, as shown in Fig. 14. A two-pass, axially directed, laser illuminated

Figure 14. Diagnostic suit for NTLX and Hydrofeatures experiments.

shadowgraph records the change in refractive index and opacity of the material as the shock passes, and a multi-frame axially directed x-ray radiograph (Fig. 15) records the change in material density as the shock moves through the medium. In principle, the change in opacity and refractive index and the change in density should be coincident. Because of radial convergence, the shock speed should increase slightly as the shock approaches the axis and the shock should reflect from the axis and expand uniformly through the once shocked medium. Simulating the reflected shock is non-trivial and these data constitute nearly the only experimental data with high enough precision to challenge the computational results. The next most challenging configuration for the simulation tools to treat is one in which the symmetrical shock in the receiver emerges asymmetrically into the inner medium. This is accomplished in the experiment by introducing an off-set between the axis of the inner medium and the axis of the shock receiver. Applying both the shadowgraph and radiographic diagnostics shows the convergence of the shock in the inner medium arriving off-axis as predicted. Taken together, these data constitute a significant test of both old and new simulation tools.
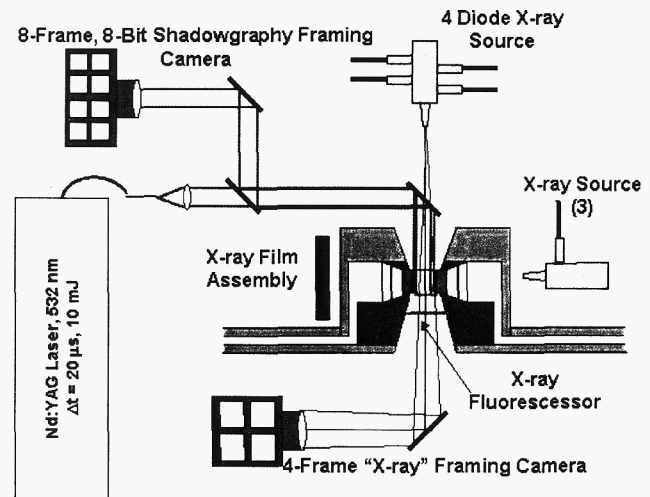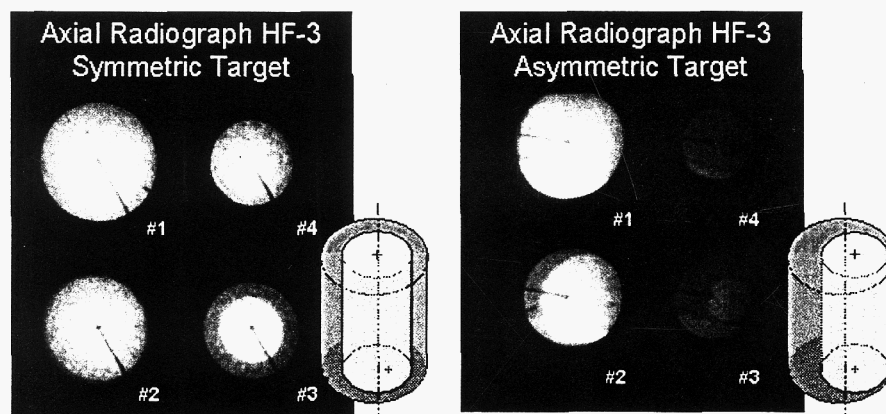

Figure 15. Axial directed radiographs of symmetric and asymmetric targets showing the convergence of the imploding shock on center (left) and off-center (right).

The imploding liner is also an excellent driver for experiments that explore the differential motion of material at an interface. Typically, experimental data on the behavior of material at "sliding" interfaces are limited to modest relative velocities and modest normal pressures. Under these conditions, the behavior of the interface is frequently characterized by a frictional coefficient similar to that used to describe a traditional mechanical system. As relative velocities between the materials increase, it is expected (and that expectation is supported by molecular dynamic simulation and by some observational data in model situations) that the material at the interface melts and the presence of liquid at the interface reduces the effective frictional force. An experiment, shown in Fig. 16, has been designed to explore parameter space where the interfacial velocity is varied from just below that for which peak frictional force is predicted (relative velocity scaled to sound speed of about 10%) to values up to three to five times that value. The first of this series was conducted on Pegasus in 1998 and the second on Atlas during this first year of operation. For these experiments, a very thick, slow-moving liner impacts a cylindrical target configured as a sandwich of circular disks or "lifesavers" with a low-density (aluminum) disk between two high-density (tantalum) disks. The converging shock produced when the liner impacts the outer surface of the target produces different particle velocities in the central aluminum, and outer tantalum disks resulting in relative motion at the interfaces while simultaneously pressurizing the target. Lead marker wires of 200 to 300-μ diameter are imbedded in 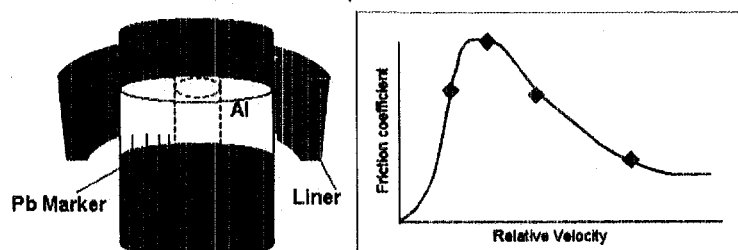the aluminum and the target is radiographed in the transverse direction as the shock converges. The thick liner provides a supported shock in the target for timescales of several microseconds. Development of the boundary layer motion is diagnosed by curvature and distortion of the wires. The experiment is performed as a function of shock strength (relative interfacial velocity), materials, and surface condition.

Figure 16. Configuration for an interfacial dynamics experiment. Atlas data will complement earlier Pegasus data

While the growth of very small-scale perturbations can be used as a diagnostic (of, for example, material strength) the behavior of perturbations, their growth rates, and ultimately their transition to turbulence, is of fundamental interest, particularly in cases where the materials undergo wide changes in properties. For example, analytic solutions for the growth of perturbations at smoothly accelerated interfaces with a density gradient (Rayleigh-Taylor) are well known.[10] The same situation with material strength has received some, but far less complete, exploration in theory and in simulation[11,12] These formulations, along with high-precision data generated from liner-driven experiments conducted on Pegasus in the last few years,[13] form the basis for the semi-integral material strength characterization experiments referred to above. When the materials properties not only involve strength, but also undergo rapid changes in material strength, such as when one component of the system melts during acceleration, the situation becomes even more complex and hence a greater challenge for both theory and simulation. Liner-driven experiments provide controllable access to such condition for exploring the fundamental behavior of such complex systems, and for providing data for benchmarking emerging simulation capability. A variation of the experimental configuration for strength characterization can be considered, in which the intermediate layer is removed and the aluminum liner is in direct contact with the perturbed copper shell. During implosion, the aluminum is melted under ohmic heating, dramatically reducing its strength at a predetermined point in the process.

Properties of Dense Plasma

The cylindrical geometry of pulseD power driven liner experiments also makes it possible to introduce materials inside the liner in a variety of interesting initial conditions. For example, a moderate density iron plasma created by the electrical explosion of an array of wires can be compressed between the driving liner and a center "anvil" to become a strongly correlated plasma. In a different vein, the liner can be filled with a magnetized fusion plasma initially formed at number density of $10^{18}/cm^3$ and 100–200 eV and compressed by the liner at velocities of 1–2 cm/μs to reach fusion ignition temperatures.

IV. IMAGING DIAGNOSTICS

Many of the advantages of liner-driven hydrodynamics experiments arise from the uniformity and symmetry of the drive and from the accessibility of the experimental volume. Together, these suggest imaging diagnostics as a principal technique for assessing the behavior of complex systems. Furthermore, as simulations, and visualization techniques associated with simulations, become more sophisticated, direct comparison of experimental data with da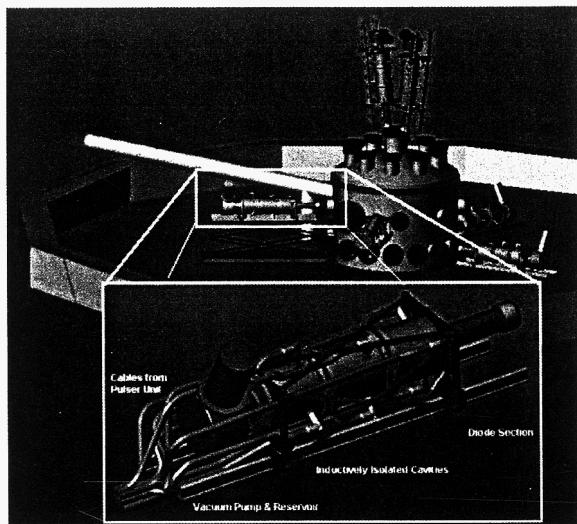ta from simulations becomes an increasingly more attractive way to demonstrate the limits of simulation capability. As seen in the first year of operation, radiographic imaging has emerged as a principal technique for diagnosing Atlas experiments and while good results have been obtained, improvements in radiography for hydrodynamic experiments is essential for future experiments. Specifically, sources with increased dose and somewhat harder spectrum are needed. A new radiographic source (Fig. 17) is under development that will use an inductively isolated cavity approach (inductive voltage adder) to provide 1.3 to 1.8-MV drive to a rod pinch diode to produce a dose of 0.5 to 1.0 R at 1 meter in a 25-ns pulse. Compact size of the source is important to allow a number of radiographic lines-of-sight to be arrayed around the liner/target assembly. It is anticipated that the development and testing of the radiographic system will require about two years.

Figure 17. Concept for an advances x-ray source for Atlas imaging diagnostics.

V. SUMMARY

The development of economical, highly reliable, low-impedance capacitor banks coupled to high-precision, near solid density liners imploding at 10–20 km/sec have made possible the development of a wide variety of hydrodynamic experiments. The uniformity, controllability, and high liner velocities enable experiments not otherwise possible and represent a complement to lasers and nanosecond pulsed power used for radiation-driven experiments.

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